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Concluding Remarks

Author(s):

GIBSON, BENJAMIN F.

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Concluding Remarks

B. Gibson *

Department of Physics
University of Colorado
Boulder, Colorado

Alamos,

Abstract. This represents the author's personal viewpoint regarding the ideas presented at this first Asia Pacific Conference on Few-Bo Problems in Physics. It is not a summary in the traditional sense, but one of emphasizing physics *not* speakers. Many of the results of these workshops are discussed.

1 Introduction

In the past few years, a number of topics have been discussed. Examples include the antiworld, metallic clusters, nuclear astrophysics, and systems.

From our viewpoint, the most interestingly of p in the 10^{-6} to 10^{-8} μ compared in the relativistic region. It is suggested that the understanding of the eventual Lamb shift measurement leading to an uncertainty in m_p which is smaller than the present uncertainty in the proton.

From the study of metallic clusters we heard about the surprising shell structure, that observed in atoms and in nuclei. Particular question of interest was whether the structure is solid or liquid. Magic numbers and the resolution.

In the area of astrophysics, explosive nucleosynthesis was the hot topic, in particular questions related to nuclear cosmochronometry and the age of the universe. Specific rare isotope measurements of ^{13}N , ^{14}O for the hot CNO cycle and ^7Be , ^8B for the solar neutrino problem. Crucially, reactions were suggested to be $^4\text{He}(\alpha, n)^6\text{Li}$ and $n(p, \gamma)^2\text{H}$.

* *Additional address:* Forschungszentrum für Kernphysik, Universität Bonn, SFB 17, D-5300 Bonn 1, Germany.

hadron dynamics. The first approach is the quark approach. An unanswered question is whether the $q\bar{q}$ pairs exchanged among the quarks in this model are related to the physical pion. The second approach is to consider complex configurations involving significant $(q\bar{q})$ components.

In the area of QCD-based χ PT of the nucleon-nucleon (NN) interaction there appears an interesting conflict. In the leading order it was established that the NN interaction is dominated by the exchange of two pions [1]. This is in agreement with the long-range part of the NN interaction. However, the short-range part of the NN interaction is not well described by the exchange of two pions. This is in agreement with the results of the lattice QCD calculations [2].

might anticipate nucleon substructure to play a role. Alternatively, effective field theory asserts authoritatively that π - π energy are not affected by short range (the quark-gluon region) in any measurable manner. Certainly, π - π energy physically of π - π nuclei.

From an NN interaction, internal interesting ts made. partition (RW analyses As) define the quality of the represent function. Given togen tich (els eff) Nuclei, equiv alent hli in analysis descriptions logical (shales derivg $\chi^2/\text{d.f.} \simeq 1$ Alternativ proac E(Ther, could to appn comparable duphahameters equiv a- lent tithyure. Evaluation taltaw as ually titativimpro vementsforac b (GDR) els then henomayological N vils promoted

the OBE hypothesis. What features of the new alternative models distinguish them from the OBE hypothesis? The longer range of the chiral perturbation theory $\pi\pi$ form of the $\sigma \cdot \ell$ term compared to that of the OBE hypothesis may be significant. The quark model in the strangeness -1 sector predicts repulsion at short range in all partial waves, rather than attraction in some as a pure OBE hypothesis suggests.

3 Few-Nucleon Dynamics

3.1 The 2 1/2 Body Problem

There are several “three-body” problems in which one of the three bodies is weakly interacting, where one does not need the power of a Faddeev-like formalism to solve the continuum problem with adequate precision. Three of these were explored at this meeting: 1) proton-proton bremsstrahlung, 2) radiative pion capture by deuterium leading to an $nn\gamma$ final state, and 3) radiative kaon capture by deuterium leading to a $\Lambda n\gamma$ final state.

3.1.1 $pp\gamma$

Precision measurements of this inelastic scattering process provide important model tests. The primary goal is the same as found in $np \rightarrow d\gamma$ or in $d(e, e')np$ reaction studies. One explores the fundamental question of what is the important physics in coupling the electromagnetic interaction with the strong interaction in hadronic systems.

3.1.2 $\pi^- d \rightarrow nn\gamma$

Pion absorption is utilized as a tool to measure a_{nn} in the final state where the interaction of the photon with the two neutrons can be neglected. The ultimate goal is a comparison of the zero-energy nn interaction with the zero-energy pp interaction, to explore charge symmetry breaking in the NN force.

3.1.3 $K^- d \rightarrow \Lambda n\gamma$

One uses the strange K^- to convert a nucleon into a Λ and the three-body $\Lambda n\gamma$ final-state to explore the low-energy Λn force. A pure two-body Λn interaction (in which there is no three-body final-state interaction) is not easily achieved by other means. The goal is separation of the 1S_0 and 3S_1 amplitudes, so that a comparison with Λp data is possible to determine the charge symmetry breaking in the strangeness -1 sector.

3.2 $N \geq 3$ Dynamics

3.2.1 The Standard Model

The non relativistic hamiltonian approach[1], in which one assumes

1) nuclei consist only of nucleons – other degrees of freedom are suppressed or treated perturbatively,

2) nucleons move slowly within the nucleus – non relativistic dynamics prevail,

3) nucleons interact primarily via pairwise forces, provides an enormous simplification and has been very successful. The dominant properties of the NN force (for lab energies of less than 350 MeV or below the pion production threshold) are:

- strong spin/isospin dependence,
- strong tensor force,
- important short-range repulsion.

Any realistic model *must* include these aspects of the force.

Extensions of the model include meson exchange currents (MEC), three-body forces (3BF), Δ degrees of freedom, relativistic effects, and quark-gluon substructure. Note that many MEC effects are of order $(v/c)^2$; that is, they are of relativistic order. Care is needed to ensure a consistent treatment of both.

3.2.2 Important Historical Highlights

For the benefit of the students at the meeting, let us review some of the historical highlights:

- Thomas' ^3H variational calculation [2, 3] of the mid 1930s demonstrated that the NN force must be of finite range – a zero range force leads to infinite binding of the three-body system.

- Tjon produced in the 1970s the initial calculation [4] of the triton from a “realistic” potential and investigated the resulting electromagnetic form factors.

- Alt demonstrated in a separable potential AGS calculation [5] that the neutron-deuteron quartet scattering length ($^4a_{nd}$) depends only upon the low-energy $^3\text{S}_1$ interaction (the spin-triplet scattering length or correspondingly the deuteron binding energy).

- Amado and co-workers demonstrated [6] the importance of analyticity and unitarity in the scattering problem, that the angular shape of the differential cross section is determined by the last rescattering but that the cross section normalization is fixed by the solution of the full integral equation.

- Finally, low energy triton observables “scale” with the binding energy of the system [1] – rms radius, Coulomb energy, D/S asymptotic normalization ratio, $^2a_{nd}$. [If one includes a 3BF to ensure a fit to $B(^3\text{H})$, then one obtains experimental values for the other observables.]

3.3 Three-Body Forces and NN Off-Shell Amplitudes

Because of issues raised at this conference, brief comments about three-body forces, NN off-shell amplitudes, and the deuteron D-state are in order:

- Potentials are not observables; that is, they are not measurable.
- NN off-shell amplitudes are not observables; they are not measurable.
- P_D , the deuteron D-state, is not an observable; it cannot be measured.

Paraphrasing the content of Ref.[7]: If there exists a local potential hamiltonian ($\sim V_{NN} + V_{NNN}$), then there exists a second hamiltonian ($\sim \tilde{V}_{NN}$ and for which $\tilde{V}_{NNN} \equiv 0$) with the same bound states and on-shell scattering amplitudes (phases), **but** \tilde{V}_{NN} is nonlocal **and** $V_{NN} \neq \tilde{V}_{NN}$ off shell. Nonetheless, particular V_{NN} models imply specific P_D and off-shell amplitudes. Data from Nd scattering, $NN\gamma$, etc. provide useful constraints on these model properties.

3.4 Prominent Issues at APFB99

A number of experimental and theoretical issues were raised at the conference:

- Nd scattering at 270 MeV: The data are beautiful. The spin observables provide a strong filter to suppress the dominant spin independent amplitudes, to permit one to examine finer details. The importance of $NN - N\Delta$ coupling and possible three-body force effects was emphasized.
- $nd \rightarrow nnp$ (coincidence studies) and A_y in $\vec{p}d$ scattering: A three-nucleon-force signal continues to be the motivation for many experiments.
- $A=4/5$ continuum investigations: Core issues in the $A=4$ system were $[31] \otimes [22]$ coupling, the n - 3H resonance structure below 10 MeV, and the question of whether the A_y problem in nd scattering has a connection with the nt cross section.
- Electromagnetic interactions of the type $^3He(\vec{e}, e'X)$, T_{20} from $^2H(e, e)$, and the measurements of G_E^n and G_M^n : The momentum transfer involved in T_{20} raises the question of the importance of relativistic effects. The use of 3He as a neutron target requires theoretical modeling.
- Chiral symmetry in the πNN system: The imposition of chiral symmetry in model calculations is recognized as an important problem.

4 Hypernuclear Physics

The physics of hypernuclei differs significantly from that of conventional, non strange nuclei. Of the many novel aspects of flavor nuclear physics some of the more interesting strangeness -1 features include:

- The ΛN interaction has no direct one pion exchange component, but it does involve significant ΣN coupling.
- The hypertriton $^3_\Lambda H$ is barely bound, in contrast to the conventional triton; ΛN - ΣN coupling in the hyperon-nucleon interaction plays a prominent role.
- The $^4_\Lambda H$, $^4_\Lambda He$ isodoublet exhibits sizeable charge symmetry breaking and a large spin-flip E_γ between ground and excited states; again, ΛN - ΣN coupling appears to play an important role.

The strangeness degree of freedom adds a new dimension to our evolving picture of nuclear physics. We should investigate whether the intuition carefully developed in the non strange sector (of conventional nuclei) extrapolates to explain the observations in the strangeness -1 sector of Λ hypernuclei **or** whether these complex models are merely sophisticated interpolation tools valid primarily within the two-dimensional (neutron-proton) isospin space where they

were developed.

There were a number of hypernuclear topics highlighted at this meeting, some involving theoretical calculations while others involved new experimental measurements:

- ${}^7_\Lambda\text{H}$ isotopes clearly exhibit the role that the Λ can play in enhancing nuclear core binding and converting resonant levels into particle-stable states.
- The beautiful γ de-excitation data for ${}^7_\Lambda\text{Li}$ and ${}^9_\Lambda\text{Be}$ (from KEK and BNL) provide new information about the ΛN $\boldsymbol{\sigma} \cdot \boldsymbol{\sigma}$ force, confirm that the ΛN $\boldsymbol{\sigma} \cdot \boldsymbol{\ell}$ force must be small (in contrast to that of the NN interaction), and illustrate through B(E2) values that the Λ compresses the nuclear core of “halo” nuclei.
- Weak mesonic decays are first cousin to neutron β decay. Rates and momentum distributions test hypernuclear model wave functions. A measurement of the π^0 decay of ${}^4_\Lambda\text{H}$ holds the key to our testing the validity of the $\Delta I = 1/2$ rule in this realm.
- Strangeness -2 data are eagerly anticipated. The existence of such hypernuclei is pertinent to the **H** dibaryon question. They provide our window to investigate the $\Lambda\Lambda$ interaction. The role of $\Lambda\Lambda$ - ΞN mixing in $\Lambda\Lambda$ hypernuclei compared to that of ΛN - ΣN mixing in Λ hypernuclei is an important issue.
- The question of narrow states in Σ hypernuclei remains of interest.
- Exotic phenomena continue to attract experimental effort: **H** dibaryon searches, stranglet searches, and searches for hypernuclei with strangeness less than -2.

Hypernuclear physics is clearly a vibrant enterprise in Japan. The experimental and theoretical efforts by nuclear physicists from our host country lead the world in this field.

5 Rare Isotopes and Unstable Nuclei

Rare isotopes with a large neutron or proton excess take us far from the line of stability and play a significant role in nuclear astrophysics. Characteristics of such halo nuclei were reported to include 1) a large interaction cross section due to the extended density, 2) a correspondingly narrow momentum distribution and soft E1 transition strength, and 3) a departure from a simple $r_0 A^{1/3}$ rule that describes stable nuclei.

For few-body physicists these properties would be expected to follow directly from the small separation energy – nothing more. Viewed in that way, the highlighted characteristics do not appear “exotic”. The hypertriton ${}^3_\Lambda\text{H}$ qualifies as one of the world’s largest halo systems: the separation energy is $B_\Lambda = 130$ keV; the distance separating the Λ from the deuteron core is some 6 times larger than the radius of the deuteron core. The complete description of ${}^3_\Lambda\text{H}$ comes from solving the same Faddeev equations that one solves to obtain the properties of the normal triton ${}^3\text{H}$; no exotic modification of the theoretical model is required. The entire difference lies in the properties of the ΛN interaction, $V_{\Lambda N}$ being much weaker than V_{NN} , which leads directly to the small Λ separation energy and corresponding extended radial distribution for the Λ .

A few other observations seem to be in order:

- The n - p force, not the n - n (nor the p - p force), binds nuclei. (If the n - p spin-triplet force were as weak as the n - n , then the triton would be bound by only about 1 MeV rather than 8.5 MeV.) Deviations of shell structure for $N \gg Z$ nuclei from that observed near the line of stability should come as no surprise; they should be anticipated.

- The mean field shell model is a phenomenological approximation, as is the radius expression $r = r_0 A^{1/3}$, developed to describe experimental observation along the line of stability ($N \simeq Z$). Deviations far from the line of stability are to be expected, when the weaker n - n force plays a more significant role.

- A Borromean system, in which there exist no pairwise bound states among the three constituents, does not guarantee a halo nucleus. ${}^9\text{Be}$ (α - α - n) is a normal nucleus and ${}^6\text{He}$ (α - n - n) is not a halo system, although ${}^{11}\text{Li}$ (${}^9\text{Li}$ - n - n) is. A halo nucleus requires only a weak valence particle interaction with the core of the nucleus. ${}^3\text{H}$ is the quintessential halo nucleus, and it is not Borromean in nature.

Despite these caveats, the investigation of shell structure far from the line of stability contains truly interesting physics. The existence and character of neutron magic numbers as a function of Z and the relationship to the neutron drip line is a fertile area of research. Study of the properties of the He isotopes represented the beginning of this field of study.

6 Summary

It is unfortunately the case in many areas of nuclear physics research that the overlap between the domain of calculations that are easily performed by theorists and the domain of measurements that are easily made by experimentalists is limited. Nonetheless, nuclear physicists are working diligently to expand the overlap between experiment and theory and our fundamental understanding of the underlying physics. We look forward to further progress in unraveling the mysteries of the nucleus by March 2000 when the 16th International few-body conference is scheduled for Taiwan.

In order to give you something to think about during the intervening months, let me leave you with a question to ponder. Everyone has heard of the classic atomic physics question: The sky is blue; what is Avagadro's number? Let me pose for you a classic few-body nuclear physics question: Why should Bethe have known in 1932 that $r_{chg}^2({}^3\text{He}) > r_{chg}^2({}^3\text{H})$, even before they were measured by Hofstadter in the 1960s? *Hint:* The answer has nothing to do with the Coulomb repulsion between the protons in ${}^3\text{He}$.

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